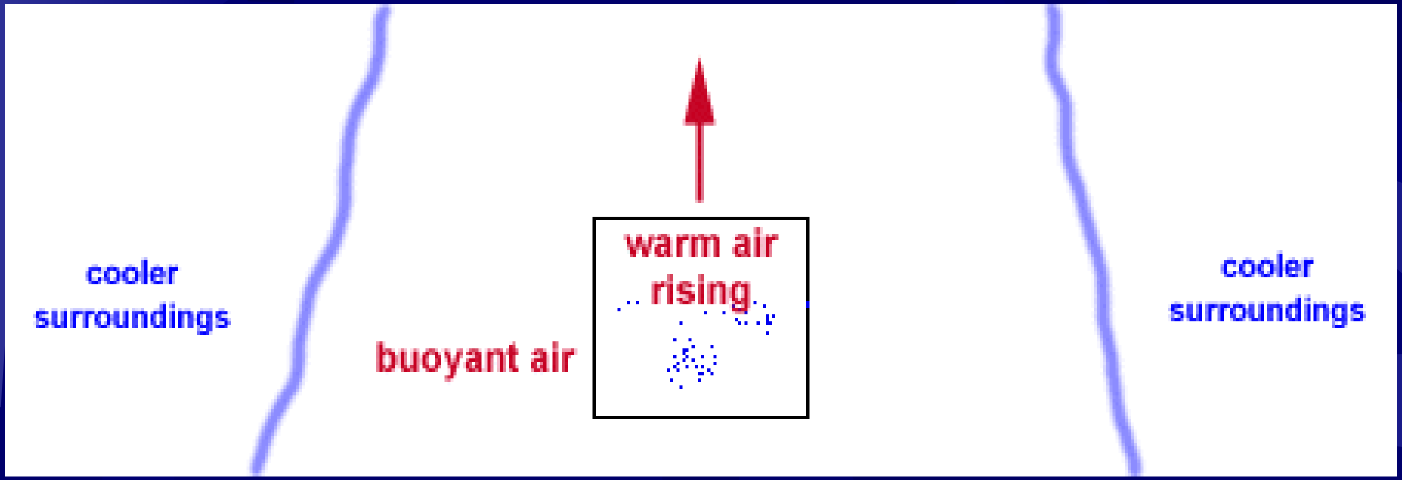
Components of Thunderstorms

Updrafts/Downdrafts

rising and sinking air

All thunderstorms require instability (potential) and lift. The lift is the mechanism that releases the instability. Lift is produced by such things as fronts and low pressure troughs, or by air rising upslope.



We say that the atmosphere is unstable when air rising in a cloud is warmer than its environment, like a hot-air balloon. It is the heat released by condensation within a cloud that permits the rising air to stay warmer than its surroundings, and thus to be buoyant through great

In the same way, air that is cooler than its environment tends to sink as long as it can stay cooler than its surroundings. The upward moving air in a thunderstorm is known as the updraft, while downward moving air is the downdraft. The atmosphere can be unstable for updrafts but stable for downdrafts, stable for updrafts but unstable for downdrafts, stable for both, or unstable for both. The degree of atmospheric instability is one of the two major factors in determining the strengths of thunderstorm updrafts and downdrafts. Furthermore, vertical draft strengths basically determine the degree of
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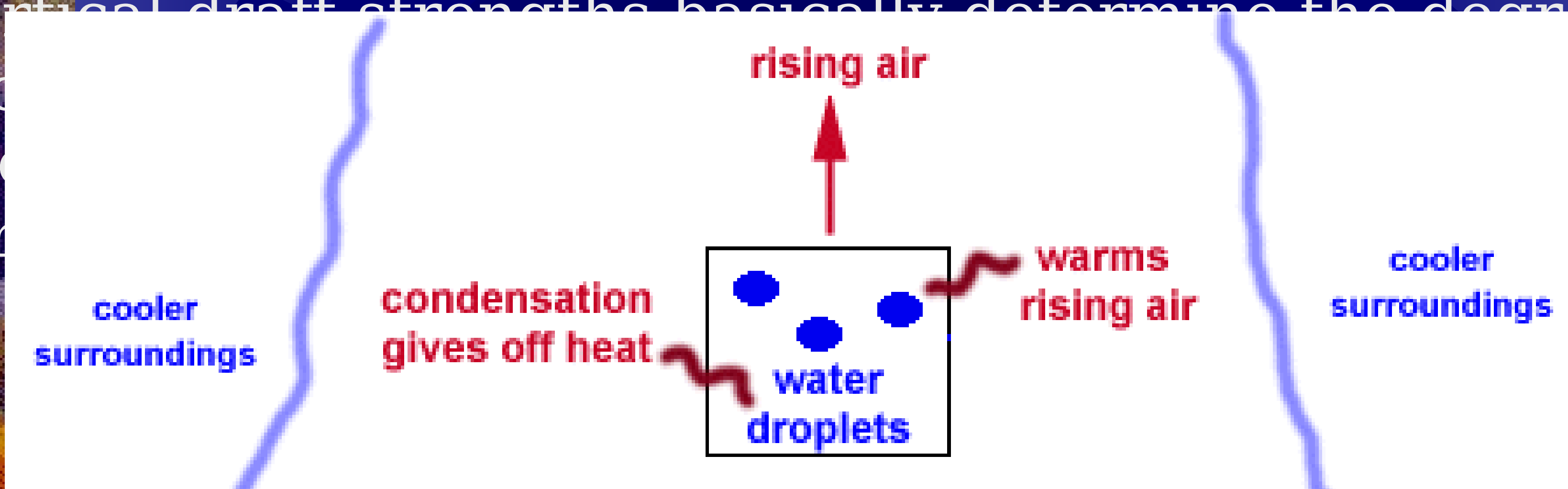
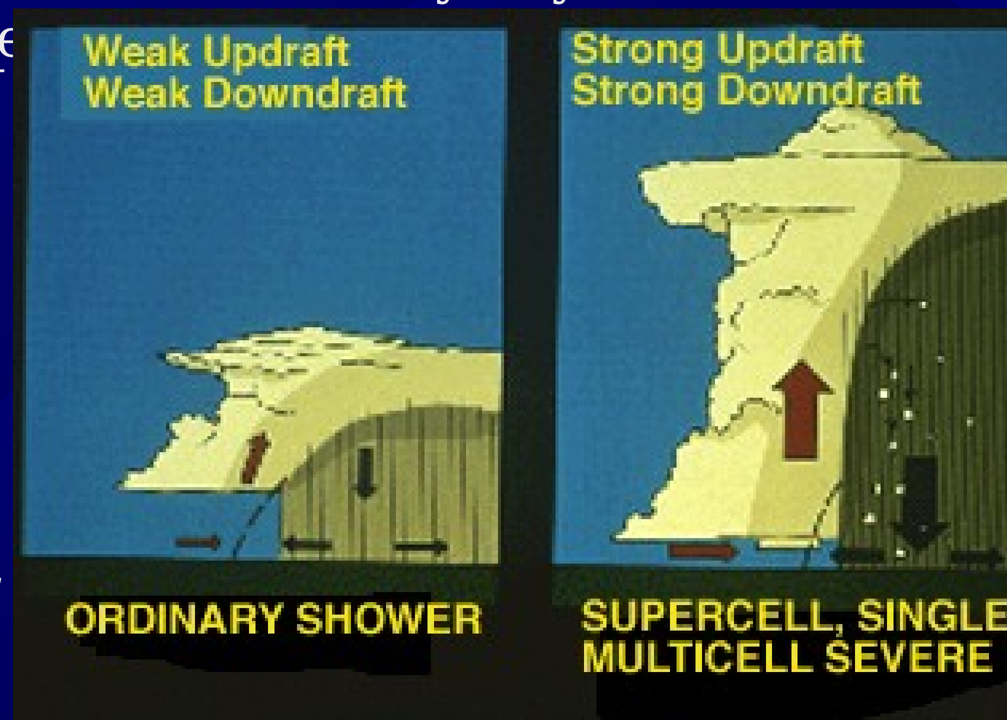


When the low-level air is unstable but relatively dry and adequate mid-level moisture is present, a storm may develop with a weak updraft but a strong downdraft with the latter the result of strong negative buoyancy and cooling through evaporation of precipitation into the dry air. This high-based storm resembles high terrain, western U.S. storms which occasionally produce dry microburst … likely.

A storm which contains a strong updraft and weak downdraft; will not produce wind damage, but can foster heavy rains and/or damaging hail. Single and multicell storms comprise this category. They include storms that dump heavy rain, but little or no hail because of warm conditions aloft, and multicell storms that are capable of producing hail because of lower environmental freezing levels. Strong updraft, weak downdraft storms often form in very moist atmospheres where there is little, if any, dry air and evaporational cooling to drive

Relatively weak updrafts and downdrafts are found with non-severe showers and thunderstorms. The last possible combination is a storm with strong updrafts and downdrafts. These storms frequently produce destructive downbursts, hail, heavy rain, and tornadoes. As one would expect, the most severe storms, including supercells, have strong vertical drafts and

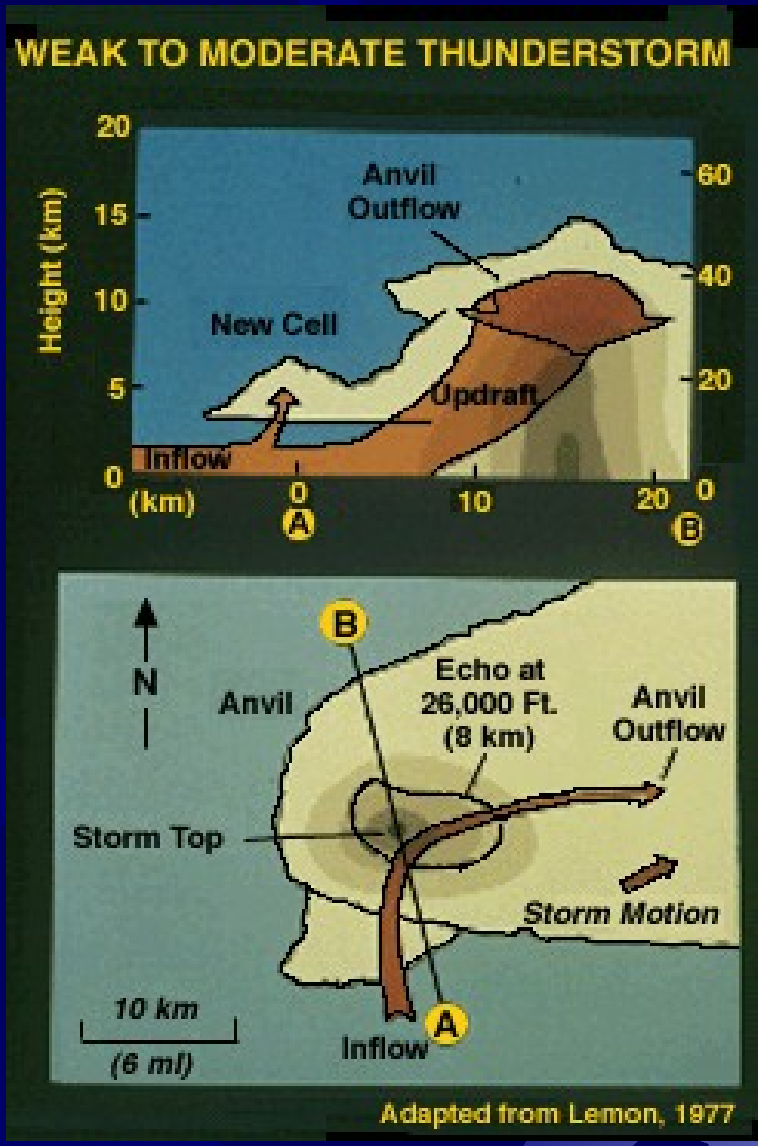


The Lemon Technique (LT)

to determine updraft strength

This section deals with the Lemon Technique of severe storm detection by radar, designed for environments with moderate to strong vertical wind shear. We have seen that strong shear causes weak updrafts to slope from the vertical, whereas stronger updrafts are able to withstand the shear and assume a more vertical character. The Lemon Technique, and modified versions such as the WRIST technique, allow the radar operator to infer the strength of the updraft through three-dimensional visualization of the radar-detectable rainy downdraft surrounding the updraft. We stress that the radar operator must perform the vertical tilt sequence employed in these techniques to determine storm structure and classification properly.

This diagram represents a weak, non-severe storm (most likely multicellular) in a sheared environment. The top figure is a westward view of a vertical cross section of the storm, whereas the bottom diagram is a horizontal, low-level cross section. (Note line A-B in the lower figure, which corresponds to the vertical cross section.) Precipitation and rainy downdraft descend downwind (usually northeast) from near the summit of the tilted cloud. The radar PPI echo, the bottom figure, has a concentric reflectivity configuration, with the highest top over the center of the low-level echo maximum. Note the orange



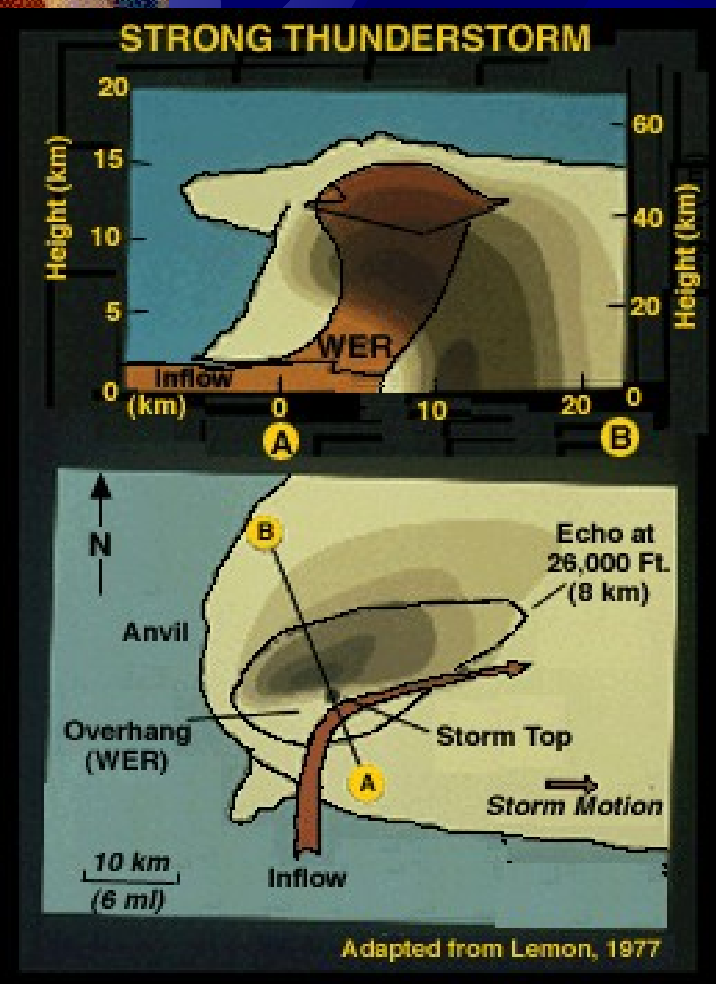
This thunderstorm was developing in a strongly-sheared environment in the northeast Texas Panhandle. The severe slope of both the updraft and its trailing flanking line towers is quite obvious in this view, looking north from about 30 miles.

One of the tops, about half way along the flank and slightly behind the first row of flanking towers, had assumed a slightly more vertical appearance. The storm was a small VIP 4 on radar at this time with its top situated over the low-level echo.

Multicell Storm Analysis

using the lemon technique

As the multicell storm becomes severe, the stronger updraft becomes more vertical and the top shifts upwind over a tightening low-level reflectivity gradient on the updraft storm flank. This transformation is not the same updraft becoming more erect with ine tower that is more powerful than



The precipitation downwind of the updraft becomes heavier, with moderately large hail (marble to golf ball size) falling near the updraft. Size separation of precipitation accounts for the increased VIP level gradient, with the lightest elements being blown the greatest downwind distance.

Tightening VIP gradient, shift in Cb top position, and development of mid-level echo overhang above a low-level weak echo region (WER) are all strong indicators of an intensifying updraft and increasing severe potential. As this intensification process proceeds, the strongest downbursts often shift from near the leading or east storm quadrant

The same Texas Panhandle storm has intensified to the severe multicell stage at this time. The tower that was on the middle-back side of the flank in the previous photograph has developed vigorously and become much more vertical than its predecessors.

The rock-hard nature of both the Cb and the downwind anvil are visual clues as to the updraft's strength. The storm was a much larger VIP 5 on radar at this time with an increasingly tight VIP level gradient on the southwest flank.

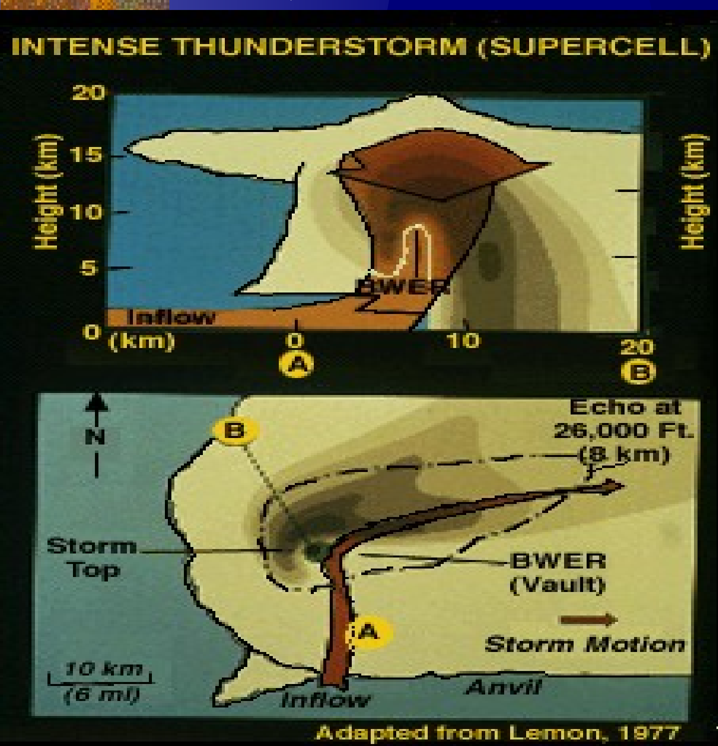
Supercell Analysis

using the lemon technique

A few storms take the intensification process further, to the supercell stage. The updraft becomes virtually erect and the storm top shifts off of the low-level echo gradient to the area above the developing pendent echo. Radar reflectivities continue to increase in both the low level and extensive mid-level overhang echoes. As mentioned earlier, evidence suggests that storm circulation associated with the mesocyclone holds the gust front in check. Therefore, rather than racing ahead of the updraft to eventually

remains quasi-stationary relative to the

continued lifting of warm air into the



A bounded WER (BWER) develops where the intense updraft is surrounded by mid-level overhang. When a hook or pendant echo is not visible on radar, a BWER often is, provided that the radar operator searches for it with the suggested vertical tilt sequence rather than with the range-height indicator (RHI) mode.

The supercell in this illustration does have a pendant echo, with the top of the rotating updraft above the WER and just east of the pendant. The radar operator must be aware that spotters are likely to see a well-developed wall cloud, often with vigorous

Why is the supercell updraft so intense? Obviously, instability is one factor. Another contributor is rotation. Research has shown that the lowest pressures in the rotating updraft initially are in the mid-levels (20,000 feet or so) in a supercell, causing an acceleration of the updraft, because of the upward oriented pressure gradient. This can result in a 50 percent increase in updr

The Panhandle storm has become virtually erect, with an extremely crisp Cb top and anvil edge. We are still looking north, from about 30 miles, at the incipient

Supercell Matures

further analysis

The storm continued to grow, and assumed an extremely impressive appearance. We are looking northeast from about 20 miles.

Was the storm really a supercell? Doppler Radar confirmed a mesocyclone. A storm chase team, looking northwest from about 10 miles, took this photograph. Note the circular banding wrapping

draft.

Again, this is visually suggestive of the rotation that Doppler Radar was indicating. The storm produced large hail and at least one tornado after this photograph was taken.

Vertical Wind Shear

change of winds with height

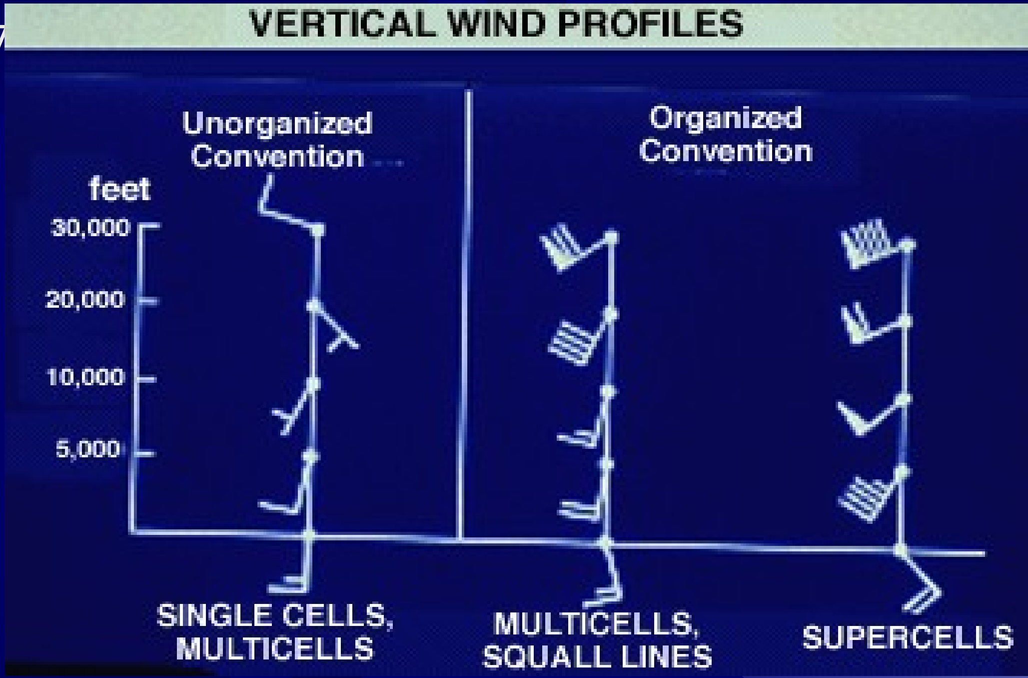
Vertical wind shear is the second critical factor in the determination of thunderstorm type and potential storm severity. Vertical shear, or the change of winds with height, interacts dynamically with thunderstorms to either enhance or diminish vertical draft strengths.

Looking north from about 15 miles, we see a storm embedded in strong vertical shear. Upper level winds near cloud summit were blowing from west to east (left to right) at 130 MPH. Surface winds were from the south at 20 MPH, indicating over 100 MPH of shear through the cloud layer! Such vertical shear often destroys all but the strongest storms by literally blowing the updraft away from its base. This nearly occurred in this case, as noted by the storm's severely tilted updraft. (It must be emphasized that cloud tilt is not always due to winds which increase in velocity with increasing height. Strong low-level winds beneath light upper-level winds will cause a cloud to slope over as the base is pushed away from the cloud tower.) Oddly, vertical shear, where winds increase or change

Thunderstorms which occur in weak vertical wind shear usually have an erect appearance. These storms don't last as long as strong storms in a sheared environment since the rainy downdraft quickly undercuts and chokes off the updraft. If any severe weather occurs with these weak-shear storms, it will be brief, occurring just prior to dissipation. Weak-shear severe storms are often called " pulse storms." (Looking southeast from 20 miles.)

organized and unorganized conv

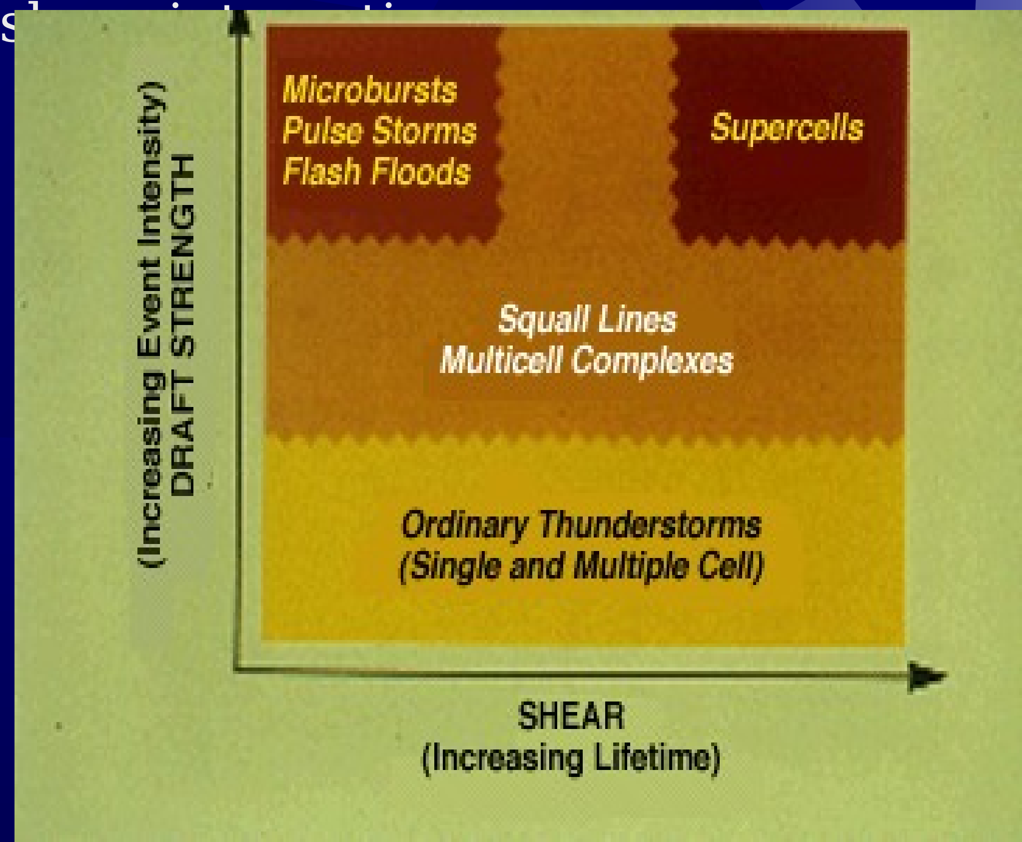
For convenience, we refer to storms in unsheared and sheared environments as unorganized and organized convection, respectively. Organized storms are longer-lived, usually have preferred areas of new updraft development, and often allow for some predictability of periodic severe weather events. Unorganized storms appear to be more chaotic, because of their nature and, to some extent, because of our lack of knowledge about them.



The examples of vertical wind profiles are similar to those that have been observed with different storm types: from the chaotic, light winds of unorganized summer storms, to the veering and increasing winds typical of organized storms. Although wind profiles of multicells and supercells appear to be similar, note both the stronger 5 to 10 thousand foot level winds and the greater low-level directional turning with supercells. These are causative factors of supercell updraft rotation. We must caution that vertical wind profiles are subject to rapid space and time changes, and better observation systems such as profilers will be important in improving practical storm-type forecasting. Also, these specific wind profiles are not

This diagram summarizes the combined effects of draft strength and vertical shear strength on storm type. Weak shears typically lead to short life cycles, although some severe weather can occur when instabilities and draft strengths are great (upper left). Stronger shears lead to longer storm life cycles, and repeated severe episodes. Note that supercells combine the strongest shears with the greatest instabilities. It is important to know that storm-relative winds are critical rather than absolute winds. Therefore, one must figure storm motion into the complex relationships concerning the thunderstorm and vertical wind s

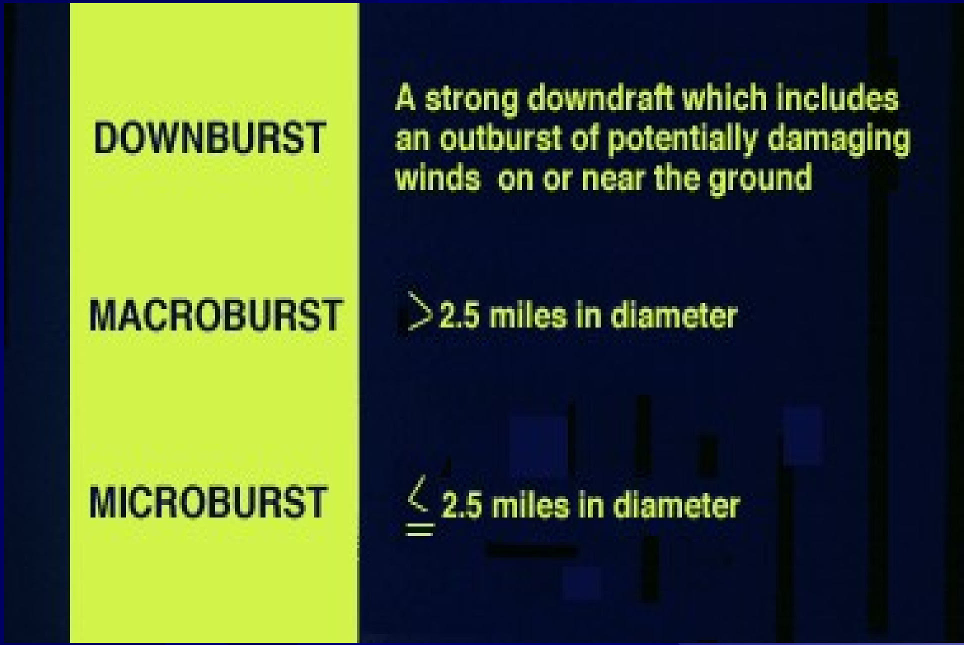
We may think of this diagram as another form of the thunderstorm spectrum. In this case, the effects of ambient atmospheric dynamics and thermodynamics on storm type are included. The information in the diagram is subjective, and we cannot assign absolute shear and stability values as partitions between storm types. Instead, we must think of the boundary and near-boundary



Outflow Phenomena

downbursts

This section is on visual identification of macrobursts, microbursts, gust fronts and other outflow phenomena. Damaging thunderstorm winds have been termed downbursts by renowned severe storm researcher Dr. Ted Fujita. Dr. Fujita further classifies these events as macrobursts (greater than 2.5 miles in diameter) and microbursts (less than 2.5 miles in diameter).



The problems that aircraft have had with thunderstorm-induced wind shear, particularly microbursts, indicate that the spotting and reporting of microbursts is of paramount importance. Although some spotters will think that events such as microbursts and flash floods are less dramatic than tornadoes, in reality, they are just as lethal, if not more so, in some circumstances. Hopefully, pilots will find these slides beneficial in identifying outflow structures that could result in dangerous approach or take-off conditions, and delay their

A downburst is a strong downdraft which includes an outburst of potentially damaging winds on or near the ground and if the diameter of the downburst is greater than 2.5 miles, then it is called a macroburst. As a macroburst or a non-severe gust front passes overhead, the ragged, concave-shaped underside of the shelf cloud accompanies the onset of cold outflow winds at the ground. Although some rotation may be visible in these clouds, it is likely to be short-lived and without vertical continuity, precluding a major tornado. Another clue for

Occasionally a cloud hole will appear behind, or in some cases immediately ahead of a gust front. The cause is frequently a small scale downdraft, possibly a microburst, which is resulting in rapid cloud dissipation.

There is little doubt about a small downdraft being the culprit in this particular case, as evidenced by the amount of blowing dust that has been kicked up beneath the cloud hole.

Gust Fronts

resembles the passage of a cold front

A gust front is a boundary that separates a cold downdraft of a thunderstorm from warm, humid surface air. Its passage at the surface resembles a cold front. A macroburst (damaging thunderstorm gust front) was advancing from northwest to southeast in this westward view across the West Texas prairie. Note the well-developed ng anvil, and the new u t front.

The question of whether or not new storms will form along a gust front is a difficult one to answer. If the gust front is moving quite fast and the atmospheric instability is marginal, new storms are not likely to develop. Research has indicated that low-level vertical shear profiles in the outflow field should be of equal but opposite sign of the shear in the low-level inflow air for the optimal redevelopment along the outflow boundary.

A telephoto shot highlights the approach of the gust front. This complex had the appearance of a haboob, a dense sandstorm that occurs along the leading edge of outflow boundaries of desert thunderstorms in North Africa. Indeed, it was dust beneath the shelf cloud that resulted in this appearance, and the

Visual Clues to Gust Fronts

cloud lowering slopes downward and away from rain area

This is the first of four photographs of an approaching thunderstorm to help visualize the difference between gust front outflow "push" and wall cloud inflow "pull." To the distant west-southwest, note the suspicious cloud lowering at the south flank of an isolated severe thunderstorm. Is it a wall cloud or a portion of a shelf cloud?

A subtle, but important clue is that the lowering slopes downward away from the rain area, rather than into the rain. This is the slope that a shelf cloud usually takes. As cold air is "pushed" out of the precipitation area by the downdraft, warm air slides up and over the gust front forming the concave-shaped shelf cloud. Within 20 minutes, the storm continued to approach. The ragged shelf

Another important clue is to discern whether or not the cloud element in question remains in one spot relative to the precipitation area, or moves away from the precipitation. When it moves away, as this cloud has, it signifies "push" and shelf cloud-producing outflow. Observe carefully, for there are signatures of strong outflow winds (a steep-sloped rain foot and a small gustnado). The storm was producing 70 MPH winds at this time.

More Clues to Gust Fronts

examining wall clouds

Still looking west from the same vantage point about 20 minutes later, the storm was moving off to the right (north) leaving a curving, weakening outflow boundary behind it. This boundary is visible as the darkest cloud base in the middle ground, arcing into the right background. Look to the right horizon. There is another rain area, and another cloud-base lowering to the south of the rain. Is this a repeat of what we have just observed? Note [illegible] oud is sloping into the rain are[illegible]

The second storm is approaching, and the cloud lowering continues to slope into the precipitation. It is a wall cloud , exerting "pull" on the rain-cooled air and maintaining its distance from the visible precipitation shaft rather than being "pushed" away from it. We have witnessed the progression from severe multicell storm to supercell when a secondary updraft in the flanking line blossomed into a rotating updraft. This storm lasted for several hours after this stage, producing large hail and several weak tornadoes.

A final word for spotters: when watching a potential wall cloud, have patience! Don't expect a quick tornado warning when you report the wall cloud, but watch for tornadic wall cloud characteristics. The forecaster and radar operator will also be

Microbursts

downburst less than 2.5 miles in
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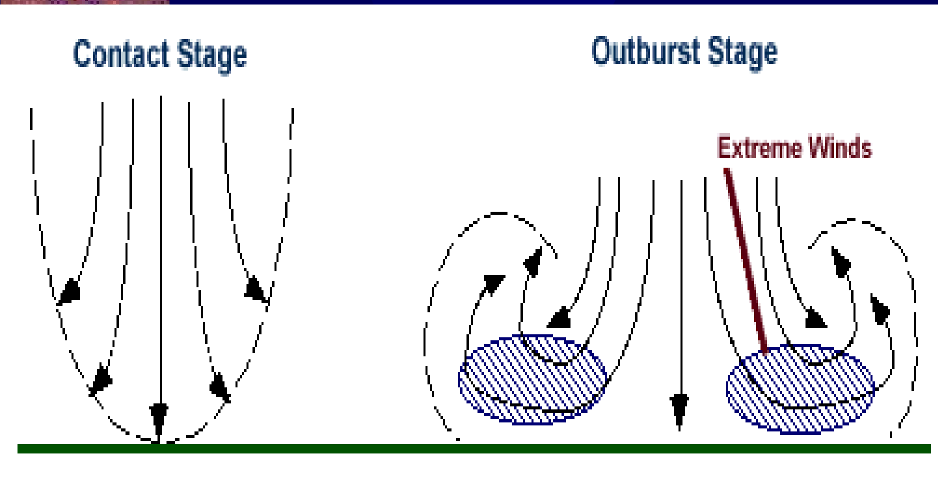
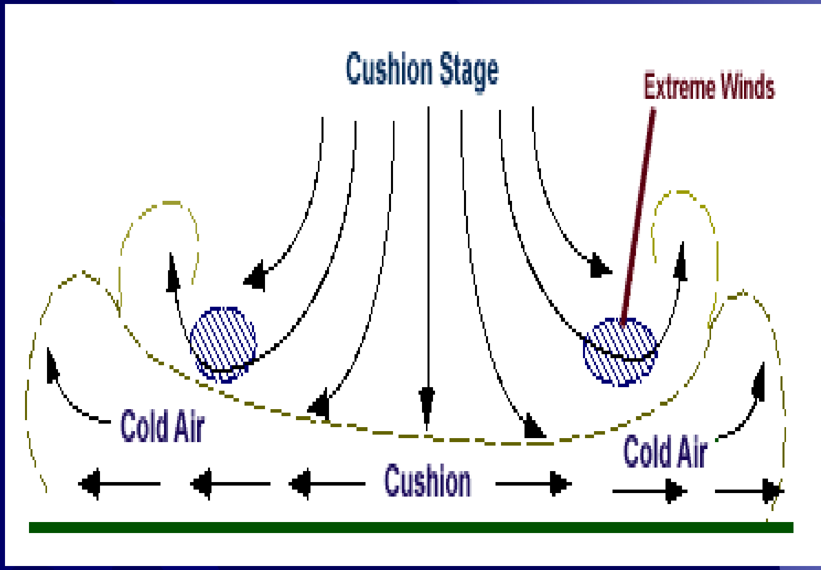


downburst is a strong downdraft which includes an outburst of potentially damaging winds on or near the ground. If the diameter of the downburst is less than 2.5 miles, it is called a microburst. The diagrams below depict the evolution of a microburst.

A microburst initially develops as the downdraft begins its descent from cloud base. The downdraft accelerates and within minutes, reaches the ground (contact stage). It is during the contact stage that the highest winds are observed. During the outburst stage (above), the wind "curls" as the cold air of the microburst moves away from the point of impact with the ground.



These are very weak, high based showers without thunder, but with microbursts. Studies have shown that they predominantly occur in the High Plains and western U.S.: particularly in unstable, very dry low level environments with surface temperature-dew point spreads of 30 to 50 degrees and an area of mi

the weak showers.

The cloud on the left is developing, whereas the fuzzy anvil on the right has matured and is producing a trail of virga. Microbursts would be most likely to occur beneath the virga, when the downdraft reaches the ground. Several of these virga

n

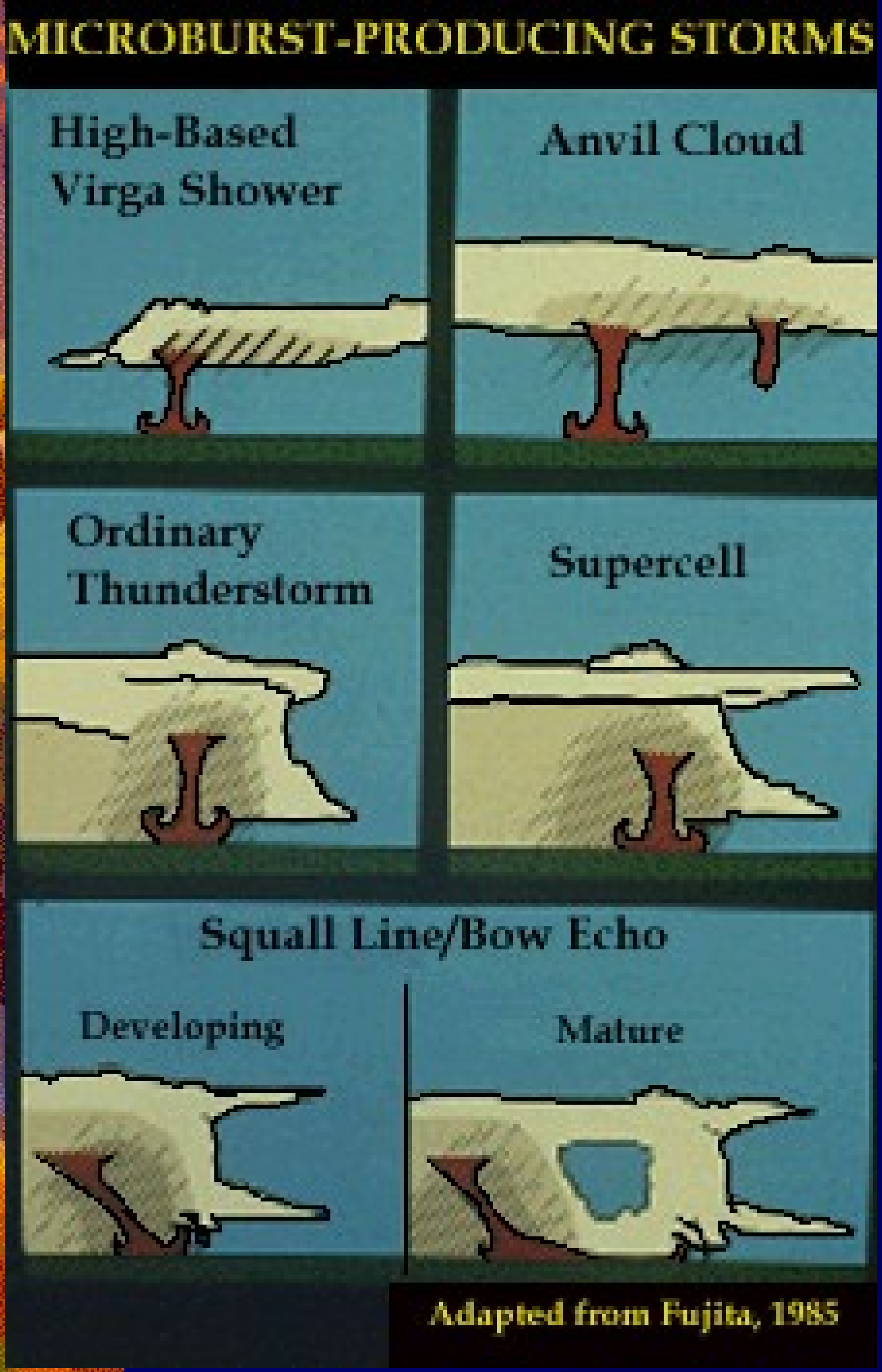
The same day, near the Lubbock Airport, we see several of the small microbursts which emanated from the virga patch in the upper right corner of the photograph. Wind shifts of 35 to 40 MPH were noted shortly after this time, with a

Anatomy of Microbursts

and the dangers they pose to aircraft

The anatomy of a microburst shows that the highest wind speeds occur shortly after the cold air has impinged upon the ground. The spin-up of the microburst curl then results in an acceleration of wind velocities about the

An aircraft entering a microburst will encounter strong headwinds, followed by strong tailwinds, as it flies from one side of the microburst to the other. If the pilot compensates for the headwind (to decrease lift) a bit too much, then the aircraft will lose lift in the tailwind and



The end of microburst danger comes minutes after the air reaches ground, but other microbursts will follow in many cases, similar to repeated tornado events with a cyclic supercell. It was determined that one airliner crashed after it encountered three microbursts in rapid succession upon final approach.

Microbursts will occur with a plethora of thunderstorm types, even dissipating anvil clouds in some cases. The important message is that some thunderstorms or even weak convective showers which were regarded as harmless a few years ago are now recognized to be

Microbursts

coupled with developing rain shaft

Developing rain shafts often have a fuzzy, bulbous appearance as they descend. If a source of dry air is present and the air into which the rain is falling is sufficiently warm, then strong, and possibly damaging microbursts are possible.

The precipitation continues to

. . finally reaching ground within several minutes. The greatest threat of microbursts will be within 5 or 10 minutes either side of the precipitation "touchdown."

Extreme Mircroburst

associated with a supercell s

This is an extreme microburst event in a supercell storm, looking west. Although no wall cloud was present, baseball hail was occurring in the precipitation shaft on the right, with a rotating updraft base in the center of the photograph. A very rapid right to left movement was

s

A telephoto view of the previous microburst shows that although there was not a full rain foot curl, there was a curl of scud clouds above the diminishing rain foot. The microburst probably was peaking or had just peaked when this photograph was taken. Remember, supercell severe weather, tornado or otherwise

Scud Clouds and Virga

minimal precipitation at the surface

Scud clouds are low, detached clouds caught in the outflow beneath the thunderstorm. As cold air first reaches the ground, it lifts relatively warm air, resulting in saturation through ascent. Thus, the presence of sub-thunderstorm base s

indicates the presence of outflow.

This is a dissipating multicell anvil cloud, looking northeast, late in the afternoon near Fort Morgan, Colorado. Note the lack of precipitation beneath the dissipating storm cell, except for

The area close to this virga could be quite dangerous for low-level aircraft operations. Microbursts that occur with virga are aptly called dry microbursts, even though a spattering of raindrops may

Rain Foot and Dust Foot

driven by ...bursts

We are looking west at the south flank of a severe multicell storm that bordered on becoming a supercell at times. Some rotation and several wall clouds accompanied the bursts of large hail and microbursts

A rain foot (right) was developing at this time, with rain-free base in the foreground and a small wall cloud southwest of the rain shaft.

Several minutes later the rain foot was beginning to curl up towards the wall cloud. Even from this distance of about 10 miles, strong winds were evident from the motions of the laterally spreading precipitation.

This seems to verify that a microburst is occurring, and also that many wall clouds likely result from an injection of rain-cooled air into the severe storm updraft.

This is not a tornado, but a microburst with precipitation being pulled into the wall cloud and updraft of the multicell st

Similar to the rain foot is a "dust foot," seen here spreading and curling upwards from left to right. An aircraft engaged in low-level operations should not venture into these rain or dust feet! Spotters should check out the area that has been affected (if possible) for any sign of damage. This was a multicell storm that also

Wall Clouds:

a lowering in the cloud base

Researchers have shown that wall clouds probably develop when some rain-cooled air is pulled upward, along with the more buoyant air, as the strengthening updraft attempts to replace ever-growing volumes of rising air. The rain-cooled air is very humid, and upon being lifted it quickly saturates to form the lowered cloud base. Thus, the wall and tail cloud probably develop sometime after an intense supercell or multicell storm begins to precip

Looking to the northwest, we see a detached scud cloud which had just emerged from the precipitation area and was moving rapidly southwestward (from right to left).

About 5 minutes later, the scud cloud entered the updraft area and was lifted into the cloud base. This was the beginning of a wall and tail cloud that persisted for over 30 minutes.

Look closely at the center of the photo and near the north end of the tail cloud. A small, tornadic dust whirl is visible. This tornado circulation was relatively weak, but strong enough to overturn a mobile home. It was beneath the tail cloud and not the wall cloud! Events such as this

Numerous observations of wall clouds indicate these following items to be the main delineating characteristics between tornadic and non-tornadic wall clouds. Tornadic wall clouds usually persist for "tens of minutes" prior to tornadogenesis, whereas non-tornadic wall clouds often don't persist as long.

Tornadic wall clouds exhibit rapid and even violent rotational and vertical (predominantly ascending) motions, with non-tornadic wall clouds having less dramatic motions. Finally, tornadic wall clouds are characterized by strong, warm inflow from the southeast and east, usually much stronger inflow than that with non-tornadic

Wall Clouds Beneath CB Towers

visual clues of storm potential

Here we have a southward view of a supercell, with precipitation in the right middle-ground and a wall cloud beneath the cumulonimbus (Cb) tower and anvil overhang in the background. The wall cloud produced a tornado wit ma City.

Looking west from 5 miles away, note the supercell wall cloud. We have learned much about the nature of wall clouds in the last decade. For instance, persistent wall clouds signify a strong updraft which is capable of producing large hail, and if conditions are right, tornadoes. However, only a few cloud-base lowerings actually are … than half of all legitimate w…

This is not to minimize the importance of wall clouds, as they are a reasonable indicator of updraft strength. The most visually-impressive examples characteristically precede the most powerful tornadoes. This ominously dark wall cloud occurred with a

Interaction with Thunderstorm Outflow

a short-lived example

This fearsome looking wall cloud to our northwest did occur with a severe thunderstorm which produced golf ball size hail and strong winds. However, within 10

to

Note the tendency for the same wall cloud to look more disorganized as it "gusted out," or was undercut by outflow.

In addition to the lack of persistence, the wall cloud exhibited little if any rotation. It completely disappeared within another 5 minutes.

Dissipating and Redeveloping Wall Clouds

indicative of multicell or non-tornadic supercell st

This small wall cloud, seen looking north-northwest from about 10 miles away, was moving south-southeast. At this time previously strong southeast winds had become near calm, and within several minutes the wind shifted to no

wa

About 10 minutes later, the same wall cloud was in the process of dissipating on the right side of the photograph. A second and equally small, unimpressive wall cloud was developing due southwest, or to the left of the first wall cloud. The second wall cloud also lasted less than 10 minutes. Once again significant rotation was not

The quick dissipation and redevelopment of these wall clouds are suggestive of a multicell or non-tornadic supercell storm. This storm did produce sporadic hail up to golf ball size and a brief gustnado along the flanking line,

Rotating Wall Clouds

indicative of mesocyclones

Here is another wall cloud on another day, looking north-northeast from about 6 miles away. This wall cloud was rotating, but periodically seemed to become undercut by outflow and lose its rotational characteristics. The storm was severe, and Doppler radar near Norman, Oklahoma, did indicate a mesocyclone, but no tornadoes developed.

We have emphasized that many thunderstorms are hybrids and contain characteristics of several of the storm classification groups that we have discussed. These storms will be difficult to warn for. The forecaster needs all the pertinent radar and spotter information that he/she can get to make an appropriate warning decision. In the case of this last storm, a tornado warning is quite probably justified, even though no tornadoes occurred. With some of the weaker wall

Looking east from about 5 miles away, a furiously rotating wall cloud was moving northeast across the forests east of Logansport, Louisiana. Spotting in the southeast and east U.S. is more difficult because of trees, hills, and typically hazy conditions.

However, the basic building blocks of storms are the same in these areas as they are around the world, although some regional differences do exist in storm structure detail. In fact, the first study of a supercell was from England, with subsequent studies coming from the Soviet Union, Canada and the United States. This storm did produce large hail, but lack of access into the

Tornadoes

violently rotating columns of air

A tornado is defined as a violently rotating column of air in contact with the ground and pendent from a cumulonimbus cloud.

They can be categorized as "weak", "strong", and "violent"; with weak tornadoes often having a thin, rope-like appearance, as exhibited by this tornado near Dawn, Texas. About 7 in 10 tornadoes are weak, with rotating wind speeds no greater than about 110 MPH. (looking west from about 1 mile.)

The typical strong tornado often has what is popularly considered a more "classic" funnel-shaped cloud associated with the whirling updraft. Rotating wind speeds vary from 110 to 200 MPH.

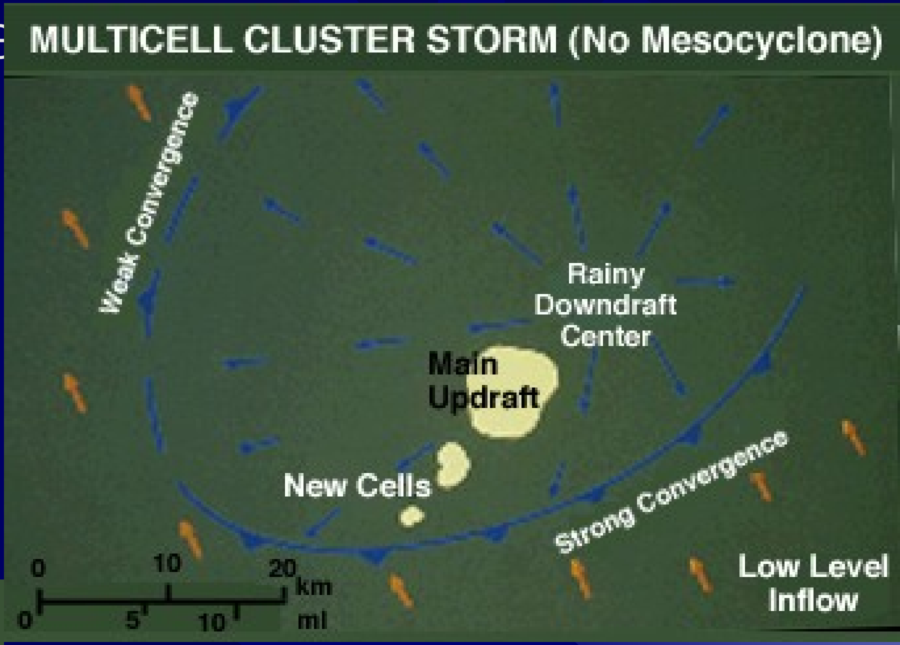
Nearly 3 in 10 tornadoes are strong, such as this twister on the plains of North Dakota. Looking northeast (from about 2 miles), note the spiraling inflow cloud, probably a tail cloud, feeding into the tornado. An important safety consideration is that weak and strong tornadoes by definition do not level well-built homes. Thus, a secure home will offer shelter from almost 100 percent of all direct tornado

Only violent tornadoes are capable of leveling a well-anchored, solidly constructed home. Fortunately, less than 2 percent of all tornadoes reach the 200+ MPH violent category. Furthermore, most violent tornadoes only produce home-leveling damage within a very small portion of their overall damage swath. Less than 5 percent of the 5,000 affected homes in Wichita Falls, Texas were leveled by this massive 1979 tornado. (Looking south from 5 miles).

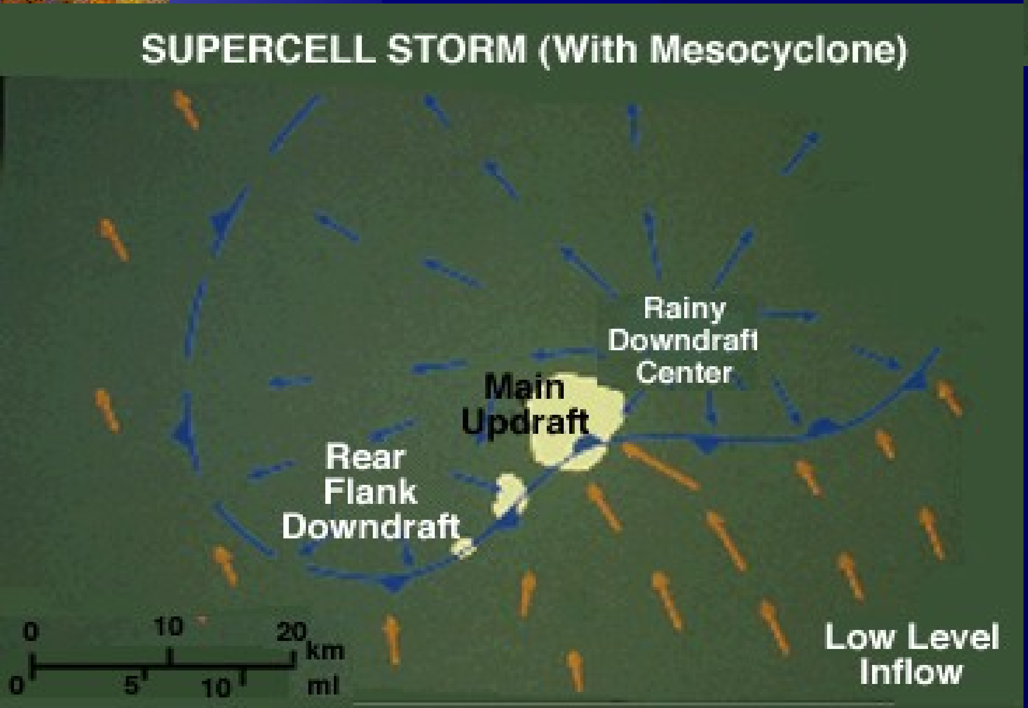
Note the huge, circular wall cloud above the tornado. This feature is probably close both in size and location to the parent rotating updraft (called a mesocyclone) which has spawned the violent tornado. Strong and violent tornadoes usually form in association with mesocyclones, which tend to

Schematic Diagrams

comparison of tornadic and non-tornadic superce

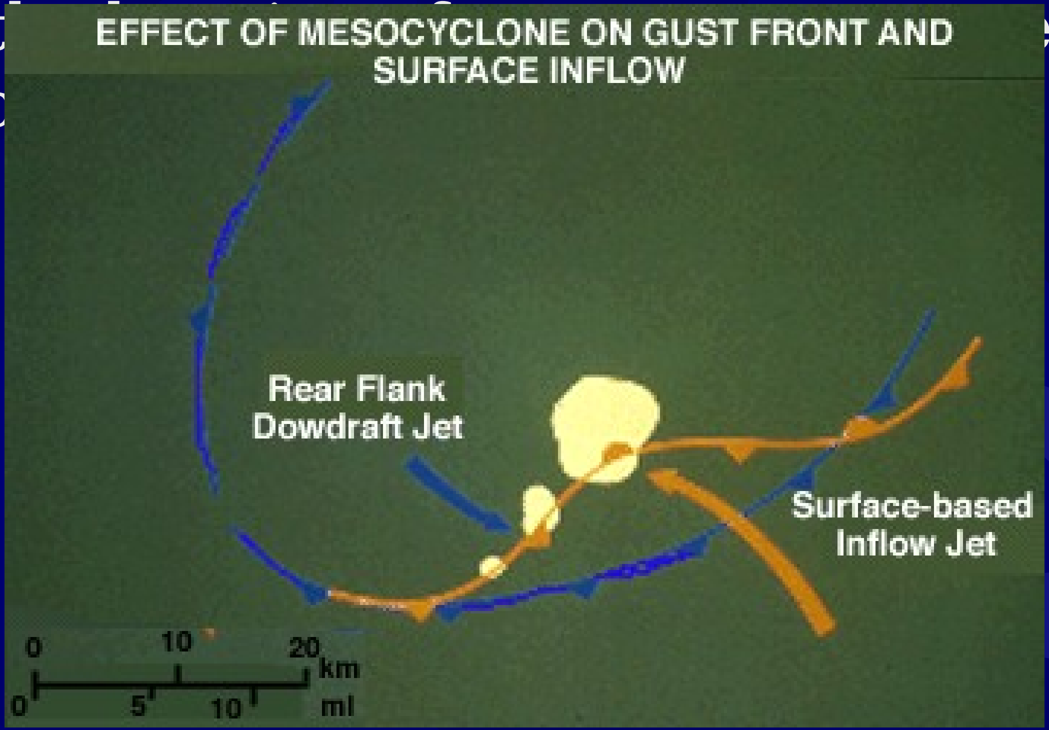


The difference between a non-tornadic thunderstorm



and a tornadic supercell is that the latter storm's vigorous rotation and surface low pressure field cause a wave to form on the gust front.

This allows warm, moist surface-based air to feed continually into the updraft and wall cloud. Cold air is "wrapped up" by the strong circulation and does not immediately undercut the wall cloud. Instead, the wall cloud becomes t ence of warm and rain-c

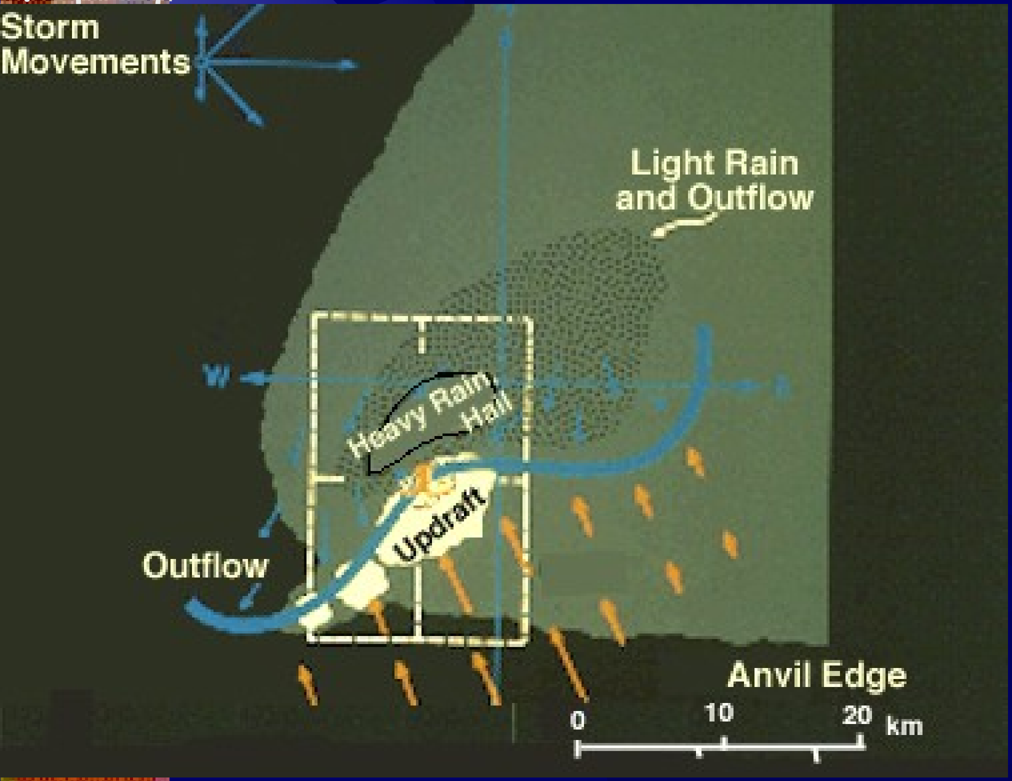


The two previous examples are combined for comparison's sake. If the "undercut" storm is a relatively weak supercell (rather than a severe multicell storm), then the circulation is not strong enough to prevent cold

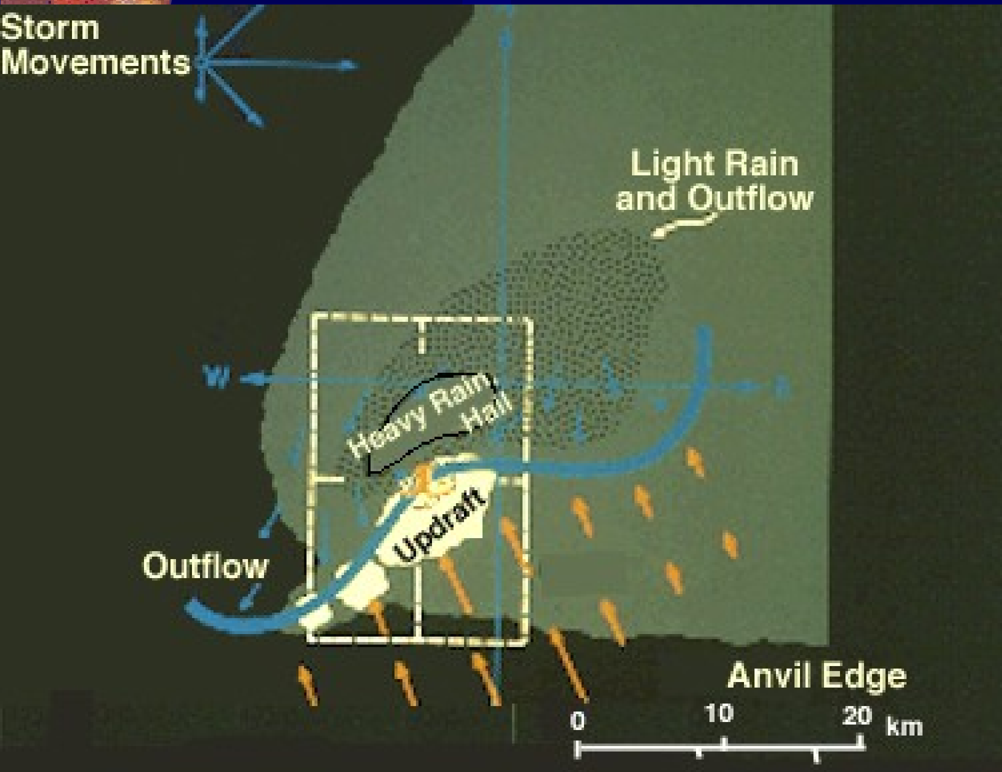
Focusing on the Mesocyclone

# of a tornadic supercell

To illustrate these points further, let us imagine that radar and spotters detect a possible supercell that is approaching a community. The spotter group's net controller first considers that the spotters must concentrate on that portion of the supercell which is most important: The quadrant with the updraft/downdraft interface.



If we center a coordinate axis and grid system on the storm's radar centroid, the "action" area typically is in the southwest quadrant as seen in this storm's horizontal cross-sectional view. Warm, ground-relative inflow winds are depicted by orange arrows and cold outflow is in blue, with the longest arrows suggestive of the strongest winds. The gust front is depicted by the thick, blue line, and the



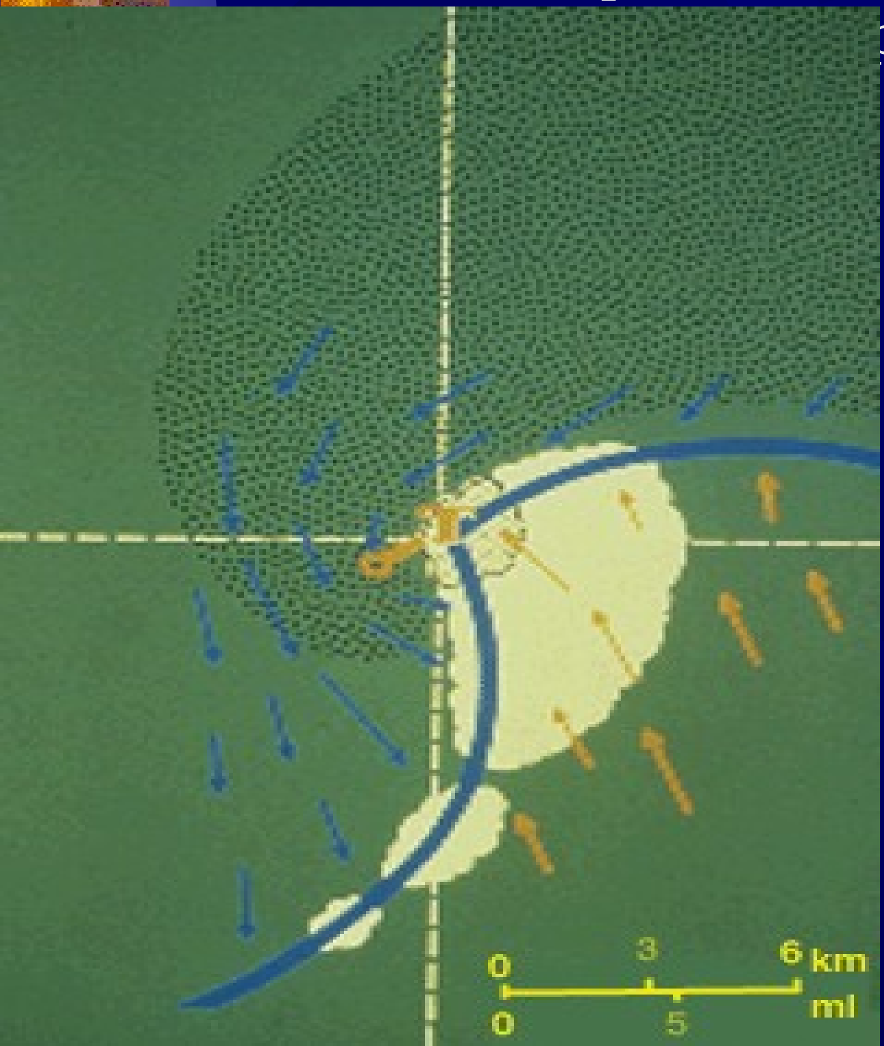
Note the storm motion vectors. Although a majority of these supercells move northeast or east, a significant number move southeast. Therefore, the heaviest precipitation usually either precedes the tornado (northeast movement) or falls immediately north of the tornado track (southeast movement), although brief bursts of large hail and/or rain often occur with the tornado.

Supercells frequently move to the "right" of non-supercell storms, even to the extreme of moving southeast on a day when winds aloft all blow from the southwest. Vigorous development on the south side of the main updraft apparently causes this rightward storm motion. Let us now concentrate on the storm flank where

Evolution of Tornadic Supercell

from early stages of tornado to dissipation

To do this, we "zoom in" and move the grid system to center it on the wall cloud and updraft area. The darkly-stippled precipitation area narrows to the radar pendant echo, that wraps around the white ...pled wall cloud.



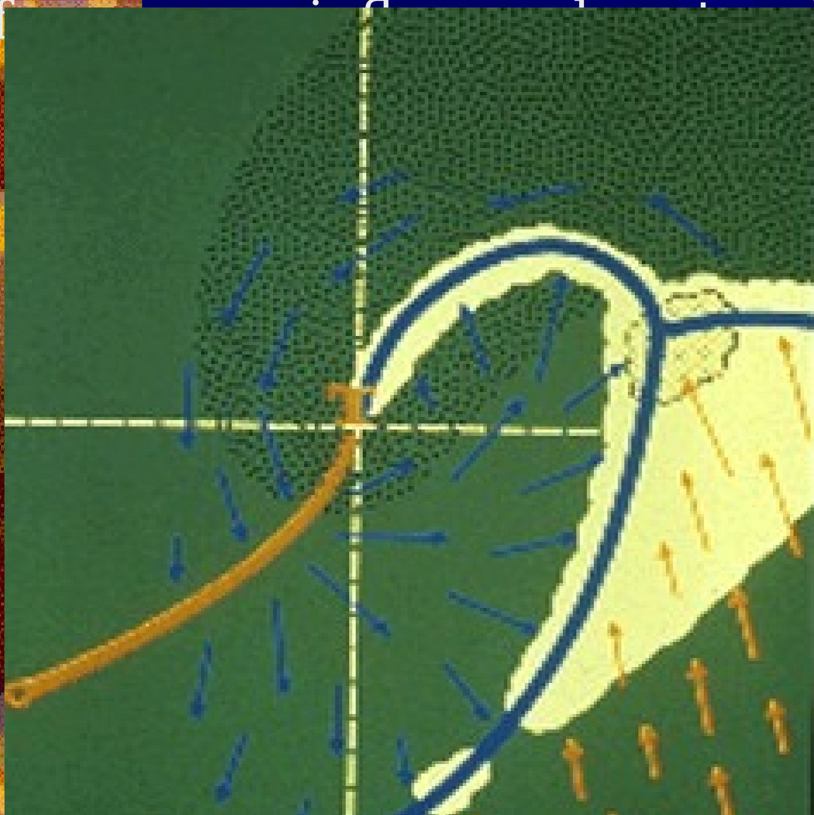
Spotter reports of strong, warm inflow winds southeast of the wall cloud suggest a higher tornado risk than the case where the wall cloud is undercut by outflow. Indeed, note the symbol "T", for tornado, and the incipient tornado track (solid orange line), indicating that a tornado has developed.

Knowledgeable spotters likely will have reported wall cloud persistence and rapid motions prior to tornado formation. We suggest that spotters have a county-wide grid system and compasses so that wall cloud positions can be readily triangulated, and that subsequent inflow and outflow circulation information can be solicited by the net controllers from spotters

During the mature stage of the tornado, the rear flank downdraft (RFD) air accelerates, causing the gust front and flanking line to surge rapidly eastward relative to the tornado. Damaging winds are possible along this flanking line gust front, and small gustnadoes often occur.

Note that radar-indicated precipitation is wrapping cyclonically around the tornado; and that the advancing gust front is cutting off warm air inflow to the tornado. Spotters south of the tornado probably would witness a sharp gust front passage.

The question mark on the accelerating gust front draws our attention to whether or not a second wall cloud is beginning to form several miles east or southeast of the existing tornado. It is extremely easy to miss such a feature with all eyes on the pre-existing tornado! The gust front has completely isolated the tornado f [illegible] dissipation is imminent



As the RFD progressively wraps around the tornado, it frequently results in a visible "clear slot" of relatively cloud-free air wrapping cyclonically around the tornado's south and east sides.

Cold air downbursts impinging upon the tornado cause the visible funnel cloud to tilt increasingly from the vertical (usually away from the rain area). This vortex stretching is partially responsible for the tornado entering into the "shrinking" or "rope" stage. It is the most likely time for the tornado to make left or right turns from its path, depending on the angle of attack of cold downbursts on the vortex.

In this example, a new wall cloud has developed several miles to the inflow side (E or SE) of the dissipating tornado. Storm spotters must be acutely aware of this possible development, which indicates a possible cyclic supercell storm, capable of producing more than one tornado. A repeat of

Superimposed Low Level Flow Field

RFD outflow and inflow fields

We have superimposed inflow and RFD outflow arrows on these two slides, again to emphasize the advance of the RFD and the eventual occlusion of the gust front.

As tornado "A" lifts, inflow and outflow convergence rapidly increases into updraft and wall cloud "B".

A Developing Supercell Intensifies

precipitation and winds intensify, rotation develops

This was initially a small supercell, looking west from about 8 miles, that packed a very intense rotating updraft. The rain curtains extending beneath the storm base were rotating, and looked very much like the rain areas we have seen under HP supercell bases. Once again, note the vaulted appearance on the north (right) side of the updraft. The storm was producing baseball size hail at this time, and a low-pitched, subtle, and continuous roaring sound w

heard this a number of time ,

and attribute it to hailfall.

Below is a northward view of the storm's main precipitation area. It has the nearly transparent look of an LP storm. The radar echo at this time showed a relatively small VIP 4 storm, although a small radar pendant was present. A VIP 4 with baseball hail! Indeed, it seemed to have m ept for the rotating rain cur pdraft base.

At this time and location, just west of Archer City, Texas, east surface winds were blowing into the supercell at 25 to 30 MPH. We are very close in position to the pseudo-warm front, separating cool outflow coming from this precipitation area to the north from warm air to the

A Tornado Develops

producing a 20 mile path of destruction

…About 15 minutes later, we have moved off to the east, but the storm is closer (relative to the photographic position) than before, about 4 miles to the west. The storm (below) was showing a dramatic visual increase in an opaque precipitation curtain northeastof the updraft at this time, which was verified by a much larger and more intense radar echo.

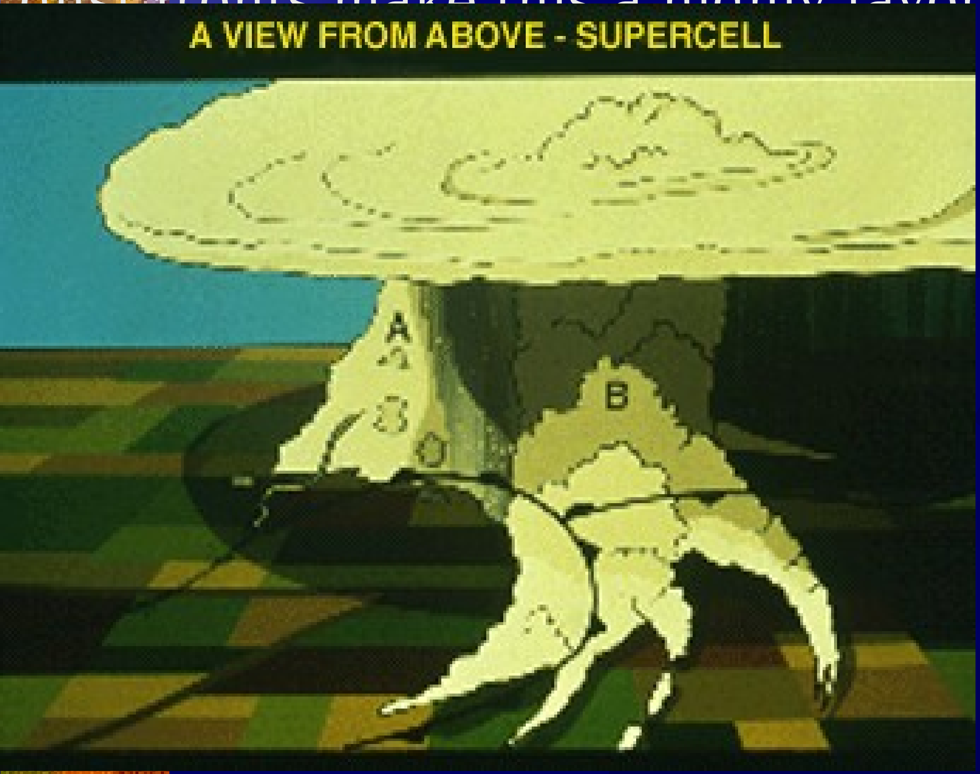
Note that the precipitation curtain extends fully around the back side of the vaulted updraft and the wall cloud lowering. From this position closer to the updraft, the easterly inflow has increased to 40 to 50 MPH! Not only was there strong inflow, it was becoming progressively stronger as it was "squeezed" into the mesocyclone. The radical increase in inflow, the increase in liquid (and likely frozen) precipitation, and the ominous appearance of the rotating

The tornado was buried in rotating rain curtains, but the rapidly-moving precipitation parted long enough to give the storm chasers this northwest view from about 3 miles. After about 6 minutes, the tornado became embedded in rain again, as it continued along a 20 mile path of destruction.

The parent storm had mainly LP traits early, then in quick succession swung into classic and finally HP storm modes. Clearly, these "variations" are spin-offs of one general storm classification, the supercell: the most dangerous of thunderstorms no matter which of the radar or visual

one updraft weakens as a new one intensifies

Looking northwest from above, an artist's view of a cyclic supercell portrays the rope stage of the dissipating tornado, and the rapidly weakening updraft (A) associated with it. At the same time, a new rotating updraft (B) is developing several miles to the east along the intersection of the RFD gust front and the stationary front (referred to as a pseudo-warm front). The juxtaposition of the intersecting gust fronts make this a highly favored area for formation of a new



The clear slot knifing between (A) and (B) and the new overshooting top indicates that (B) is now the dominant updraft. The cyclonically curving cloud bands inflowing to (B) and a "beaver's tail" oriented east-west in the cloud shadows near the pseudo-warm front are important visual supercell signatures that

From a meteorological view, as the cool and warm air on adjacent sides of the pseudo-warm front rush westward into the mesocyclone, there is a tendency for the north side cool air to slide beneath the warm air, which, in turn, rotates above the cool air. This "solenoidal" generation of horizontal vorticity and subsequent tilting of this vorticity into the vertical may be a vital component of the tornadogenesis process.

Looking in the same direction (northwest), but from beneath the storm, we observe another mature tornado with a clear slot RFD wedging in between the wall cloud and flanking line. A large area of rain-free base is apparent to the east of the tornado.

About 10 minutes later, the tornado lifts after its inflow has been cut off by the advancing RFD. A new wall cloud (extreme right) has formed from beneath the rain-free base, 3 or 4 miles east-southeast of the dying tornado. Within about 20 minutes this wall cloud fostered a violent, 1 mile wide tornado. These tornadoes occurred in the Alfalfa and Binger, Oklahoma. A limited amount of data indicates that 20 minutes is about average for

More Tornadoes produced by cyclic storms

Yet another cyclic storm, looking towards the northwest. Visibilities and contrast were low in this northern Kansas storm, but we can make out a distant, rope-like tornado just left of center (about 6 miles to our west-northwest, and a wall cloud and developing funnel on the extreme right, about 3 miles to the north-northwest.

Minutes later, tornado #2 has touched down to our north-northwest whereas tornado #1 has lifted. This second tornado was producing significant damage at this time.

Moving closer, we are looking north from within 1/2 mile at tornado #2. It was changing rapidly in appearance as it quickly evolved into a large multiple vortex tornado. The huge vortex to the right of the road developed and dissipated within a minute, as another sub-vortex was forming to the left of the road. The tornado had become violent and leveled several farms. Early warnings wer
rep

Below is a storm which seemed to defy most of what we have said about cyclic storms! Looking north, note tornado #1 (with clear slot) at the south end of the precipitation area, tornado #2 east of the precipitation (extreme right), and wall cloud/developing tornado #3 in the visual distance between #1 and #2, and northeast of the precipitation area!

Thus, instead of a 20 minute gap we have concurrent mesocyclones on three different thunderstorm flanks! There are always exceptions to just about any "rule of thumb" we can make about severe thunderstorms.